ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

Safety assessment of nanomaterials for industrial application

Health Safety Assessment of Nanomaterials for Industrial Applications: state of the art and research needs

Francesca Pacchierotti - ENEA, Rome

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Nanocomposites

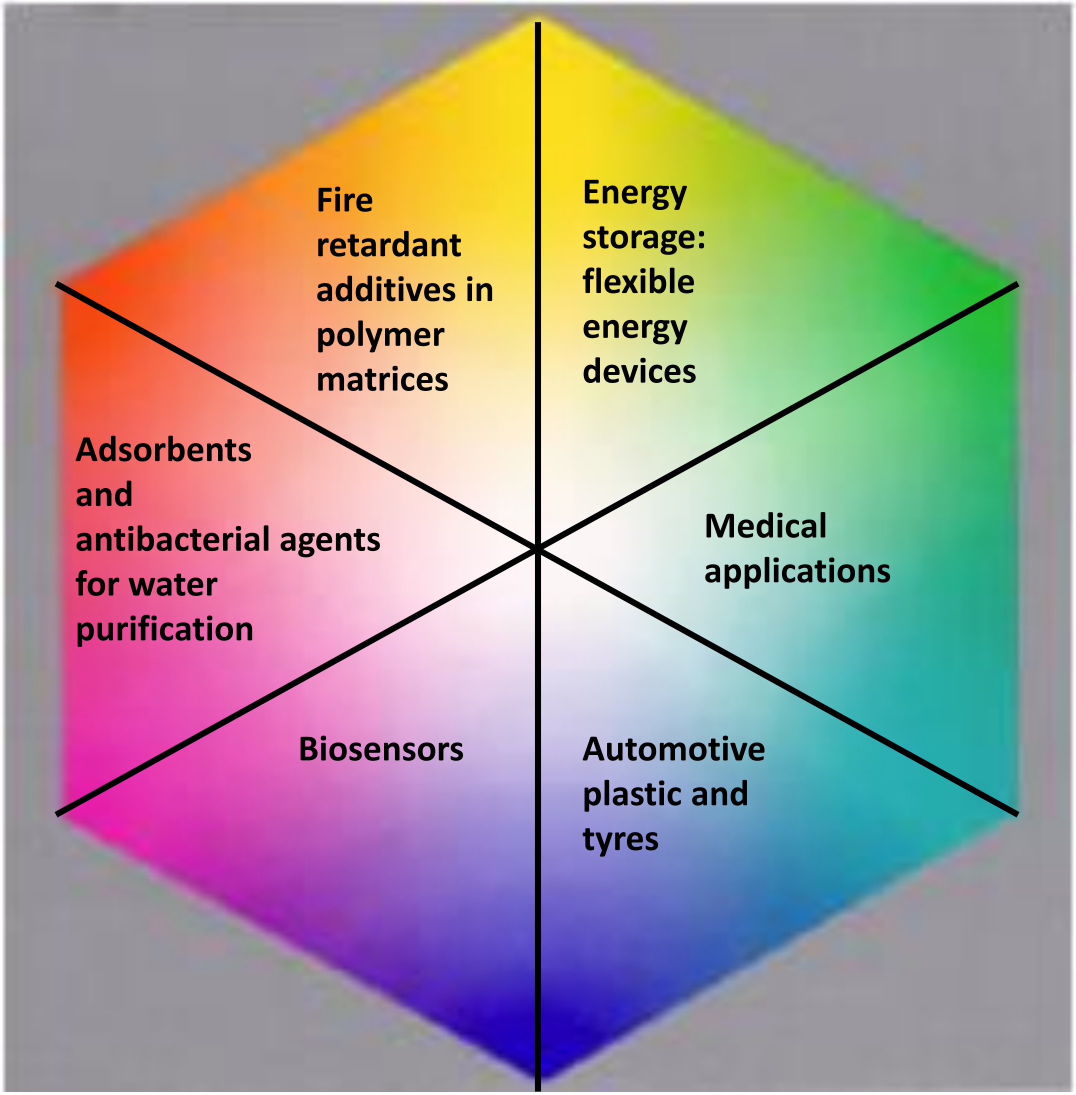
NANOCOMPOSITES are multicomponent systems where materials are combined with ENM.

ENMs can be incorporated onto the surfaces of applications or into a material's matrix.

ENM, even at small concentrations, can dramatically enhance material properties, such as scratch resistance, elasticity, conductivity, etc.

These new materials, often called NANO-ENABLED PRODUCTS, are already being used in the place of conventional composite materials.

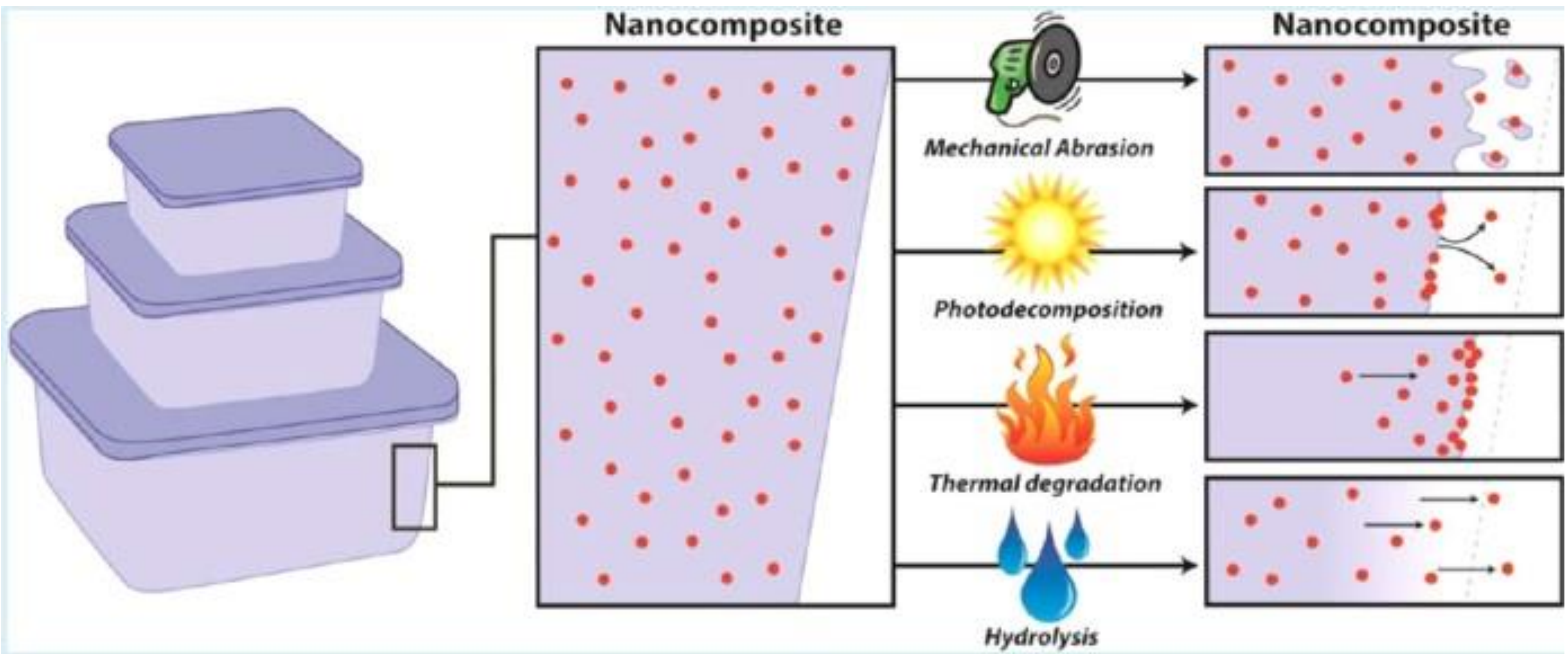
Nanocomposite applications



Nanocomposite toxicology

Which factors may influence the potential toxicity of nanocomposites

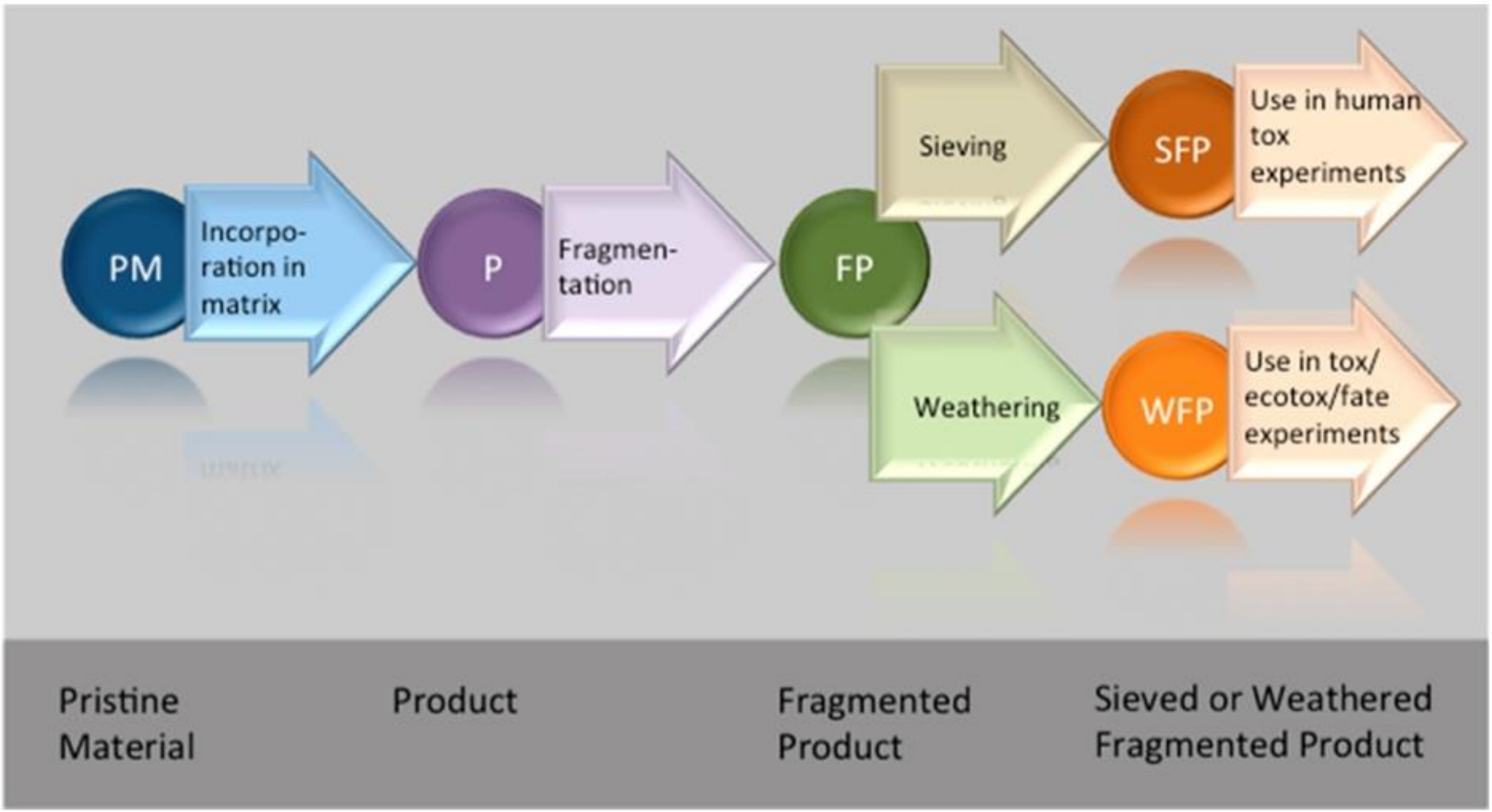
- Matrix
- Characteristics of pristine ENM (organic vs inorganic, spherical vs fibrous …)
- Degradation processes (mechanical, physical, chemical, biological)



Duncan et al., ACS Appl. Mater. Interfaces 2015, 7, 20!39

Modeling reality: real stuff, life cycle, weathering, release …

EU Sustainable Nanotechnologies Project



Release of nanomaterials from solid nanocomposites

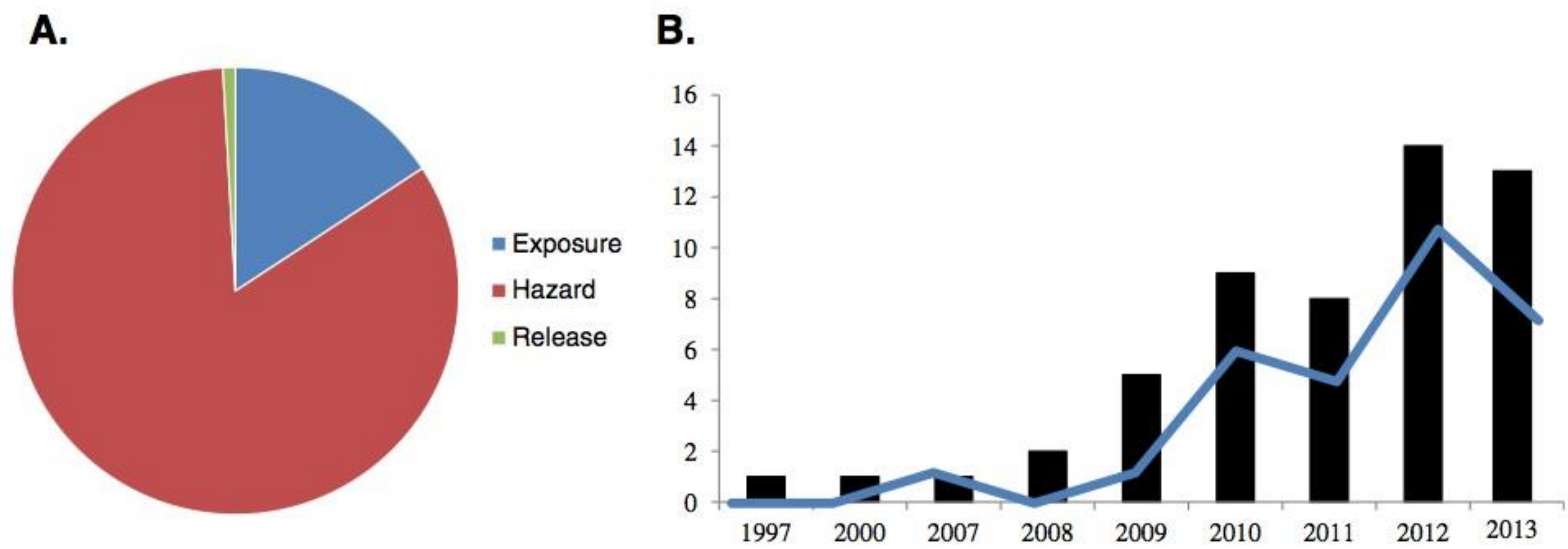
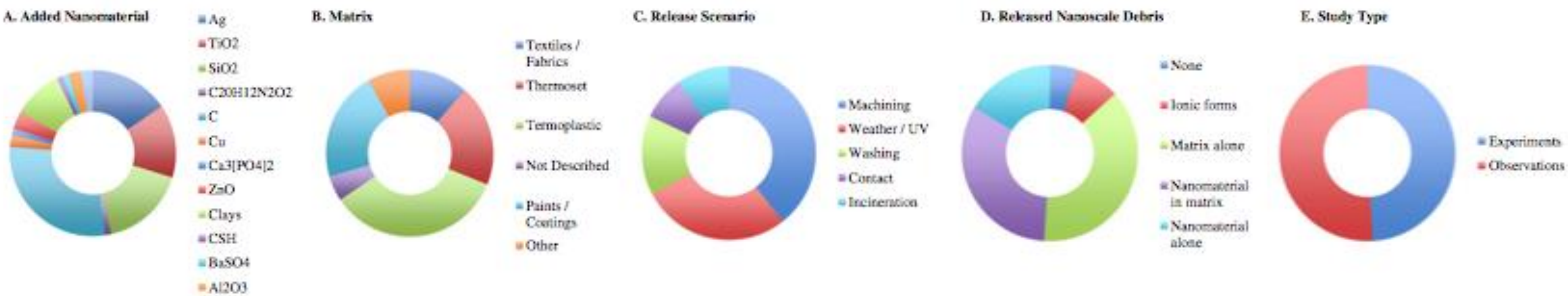


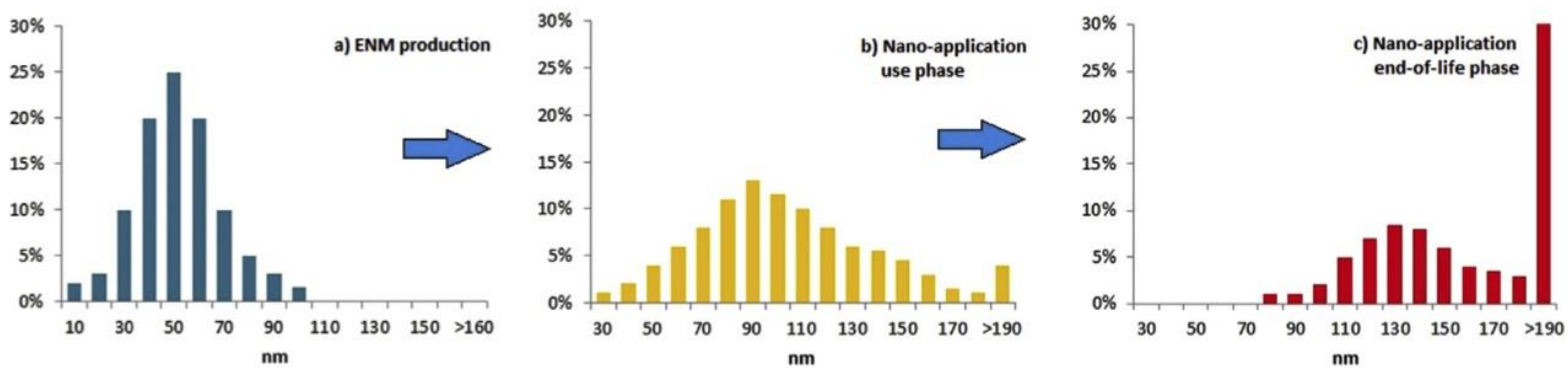
Figure 1 Published literature on release form nanocomposites. The "nanorelease" picture in terms of how many research articles have been published. **(A)** Using the ICON online database of nanotechnology environmental health and safety research, we report the number of articles identified by the "exposure" and "hazard" search terms, and compare these to the release studies we identified through multiple search engines. Considerable attention has been directed toward examining intrinsic hazards (83%) of nanomaterials, and less on potential exposure (16%) and least on release from nanocomposite (0.8%). **(B)** Since the first nanorelease study we identified in 1997, understanding release from solid, non-food nanocomposites has received increasing attention (bars) and an increasing number of these studies have been rigorous experiments (line).

Froggett et al. Particle and Fibre Toxicology 2014, 11:17

Release of nanomaterials from solid nanocomposites



- Calls for method validation and standardization
- How laboratory release scenarios relate to real-world conditions
- Fate and transport modeling



Froggett et al. Particle and Fibre Toxicology (2014) 11:17
Caballero and Nowack, Environmental Pollution (2016) 213:502e517

Table 5 – High-level summary of considerations for material characteristics of MWCNT–polymer systems (epoxy, PC, PA, PU, PE) as relevant to release potential.

	Epoxy	Polyamide	Polyurethane	Polyethylene	Polycarbonate
Mechanical Characteristics	Hard, brittle	Soft, ductile	Soft, ductile, elastomer	Soft, ductile	Hard but ductile**
Photodegradation	Rapid, CNT can stabilize	Susceptible	Susceptible	Low	Susceptible
Oxidation	Susceptible	Susceptible	Susceptible	Susceptible	Susceptible
Hydrolysis	Susceptible	Susceptible	Susceptible	Low	Susceptible (esp. when exposed to base)
Thermolysis	Low	Low	Low	Low	Low
Mechanical Degradation	Low	Low	Low	Low	Low
Lifecycle*	End of life processing	End of life processing	End of life processing	End of life processing	End of life processing
Summary	Low	Low	Low	Low	Low

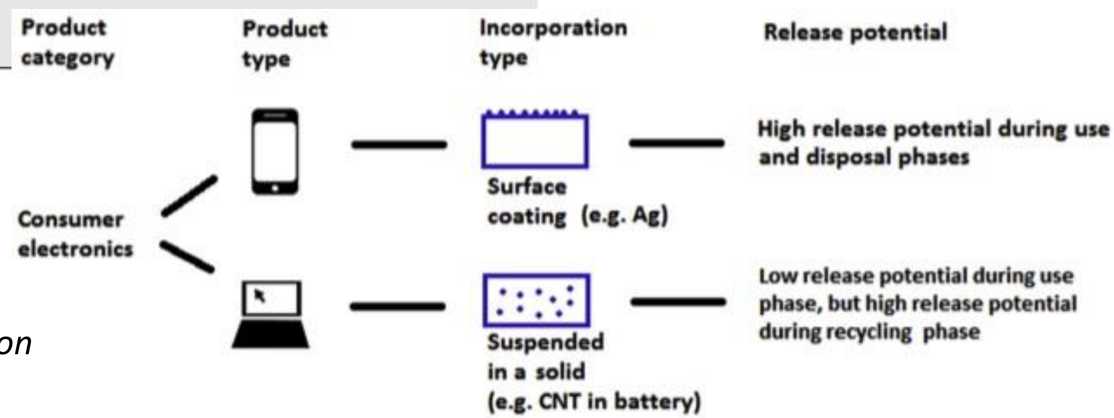
Green – low susceptibility for release; yellow – moderately susceptible for release; red – high susceptibility for release.

*Life cycle stages most relevant for degradation which can influence release potential. The manufacturing stage is not considered in this report.

**Increasing brittleness with higher loading of CNT.

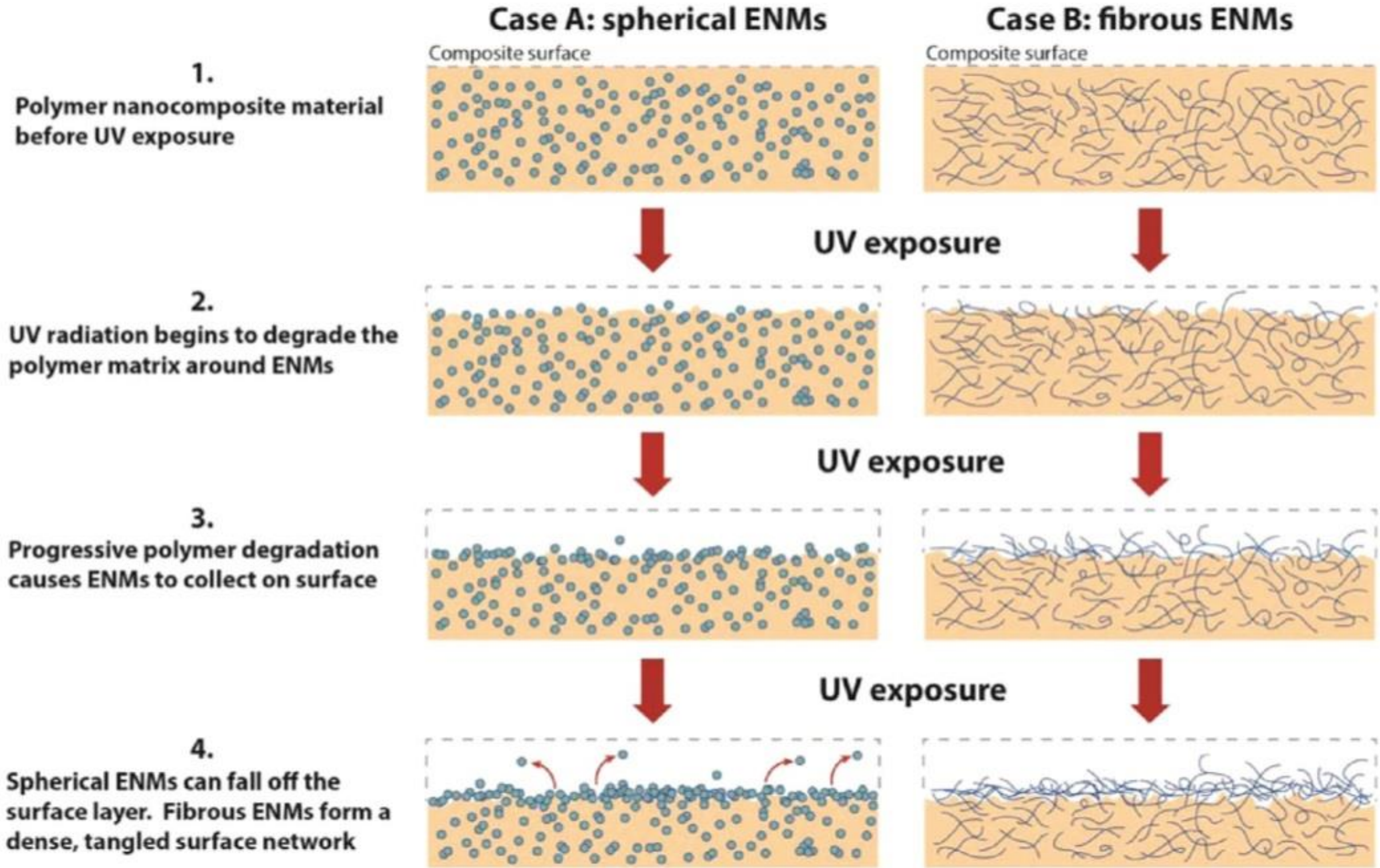
"Evidence to date suggests that it is fairly unlikely that free MWCNT will be released, but that CNT embedded in or attached to small polymer fragments is the most likely form of release"

Kingston et al., Release characteristics of selected carbon nanotube polymer composites, CARBON (2014) 68:33 – 57



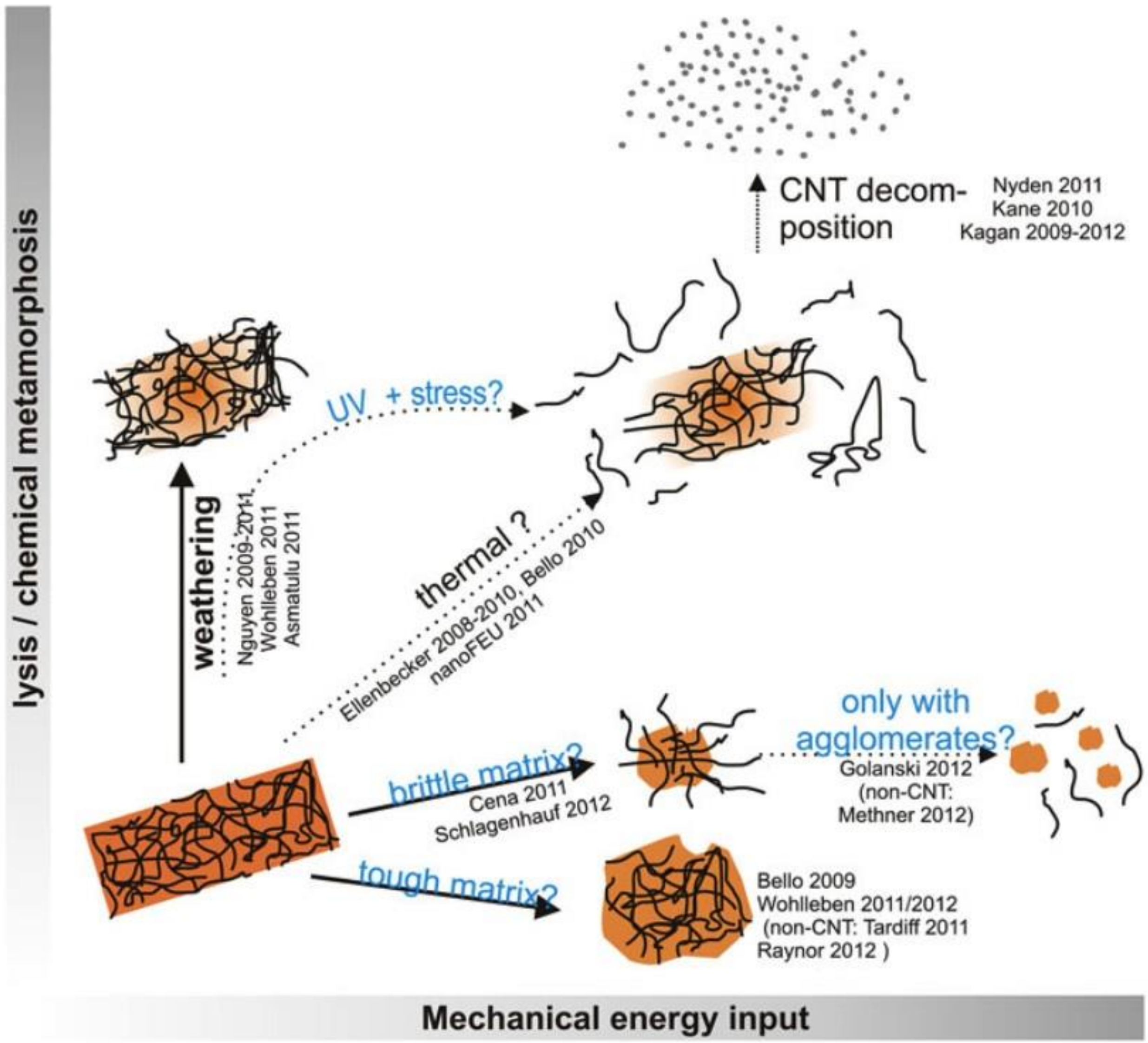
Caballero and Nowack, Environmental Pollution (2016) 213:502e517

Release potential: effect of ENM shape



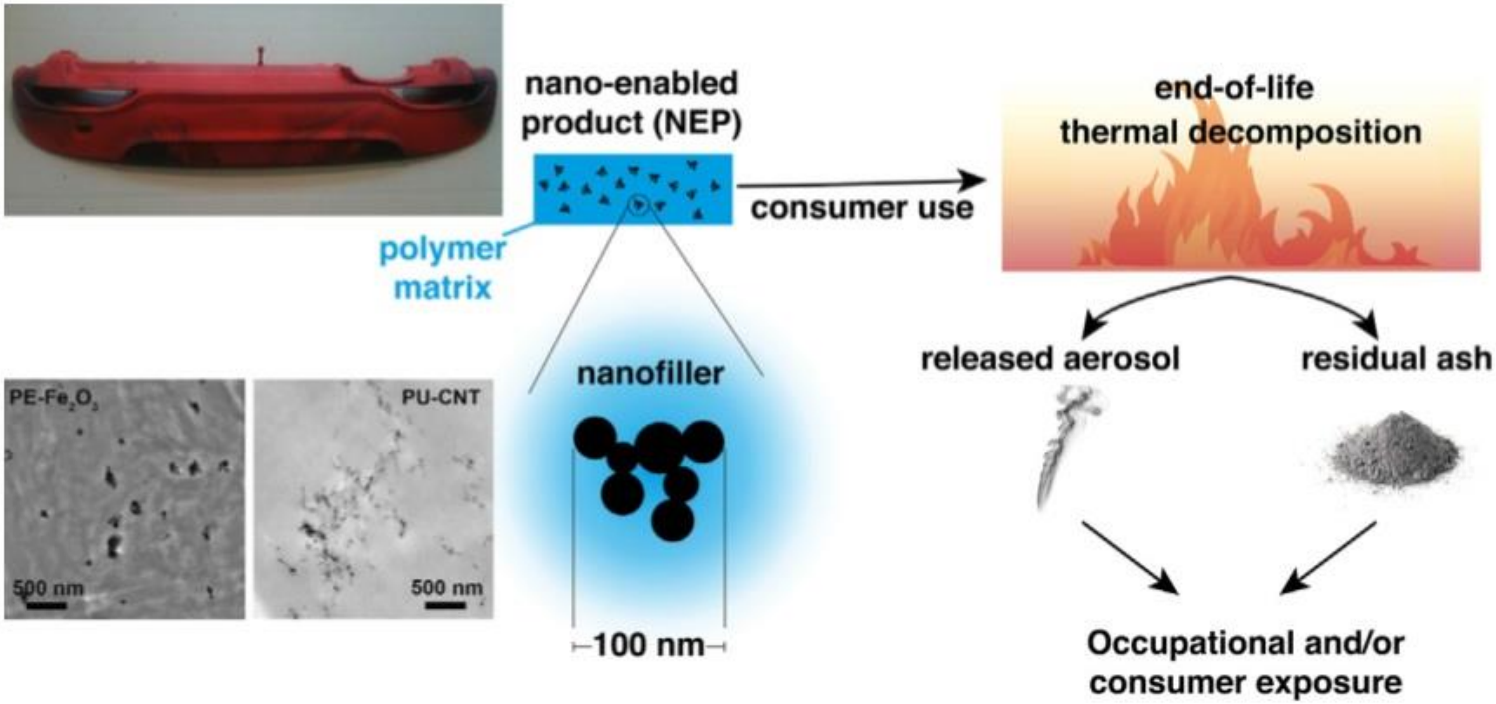
Nguyen, et al., Fate of nanoparticles during life cycle of polymer nanocomposites. J. Phys. Conf. Ser. 2011, 304, 012060(1−12)

Release potential: effect of degradation processes



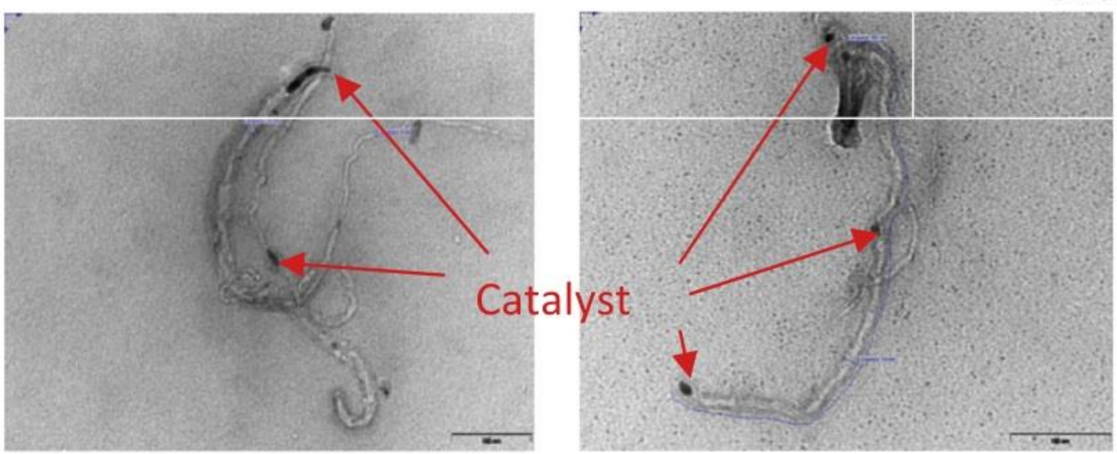
Hirth et al., Scenarios and methods that induce protruding or released CNTs after degradation of nanocomposite materials. J Nanopart Res (2013) 15:1504

Release after thermal degradation



Sotiriou et al., Thermal decomposition of nano-enabled thermoplastics: Possible environmental health and safety implications.

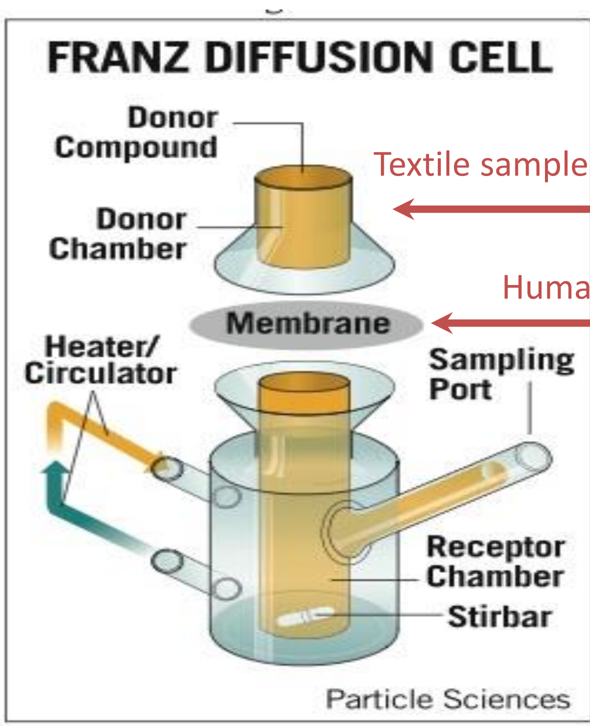
Journal of Hazardous Materials 305 (2016) 87–95



This study has shown that at quite low temperatures (about 400 ° C), the combustion of nanocomposite polymers, made of ABS matrix filled with 3% of MWCNTs, released MWCNT nanofibers in the gas phase.

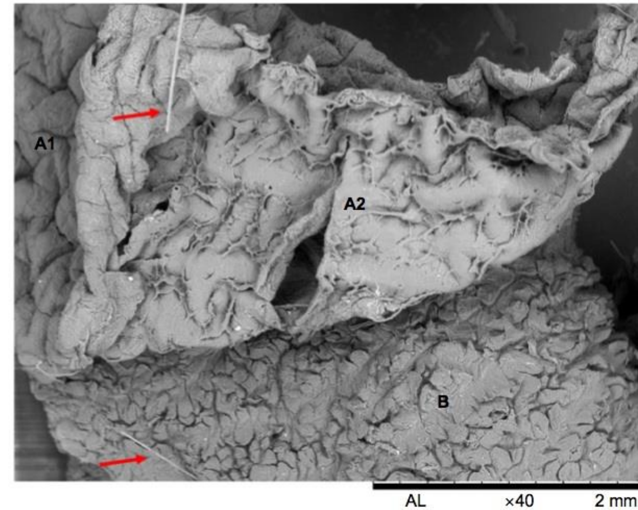
Bouillard et al., Nanosafety by design: risks from nanocomposite/nanowaste combustion. J Nanopart Res (2013) 15:1519

Release and skin absorption of NPs from textile composites

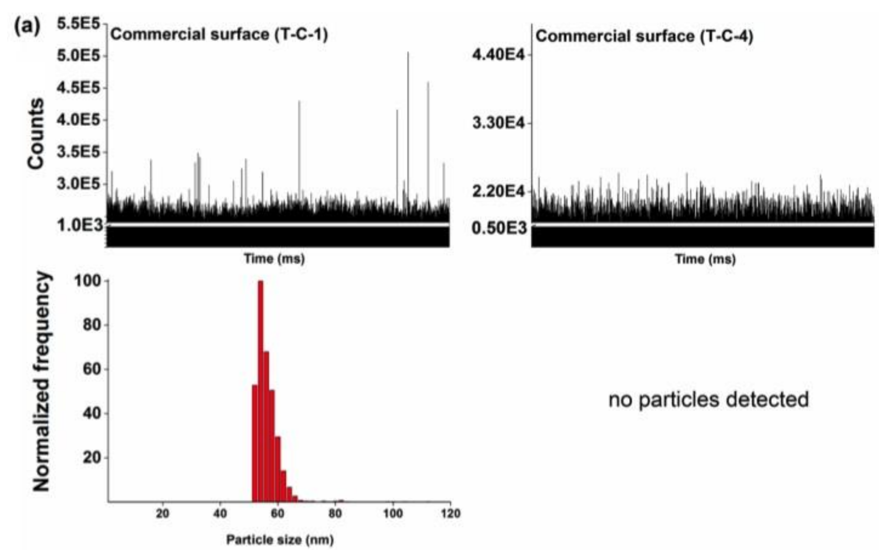


Textile sample soaked in artificial sweat

Human cryopreserved skin



Micro-sized Ag-positive aggregates in the epidermis and dermis



Bianco et al, In vitro percutaneous penetration and characterization of silver from silver-containing textiles
Int J Nanomed 2015:10 1899–1908

Wagener et al., Textile Functionalization and Its Effects on the Release of Silver Nanoparticles into Artificial Sweat

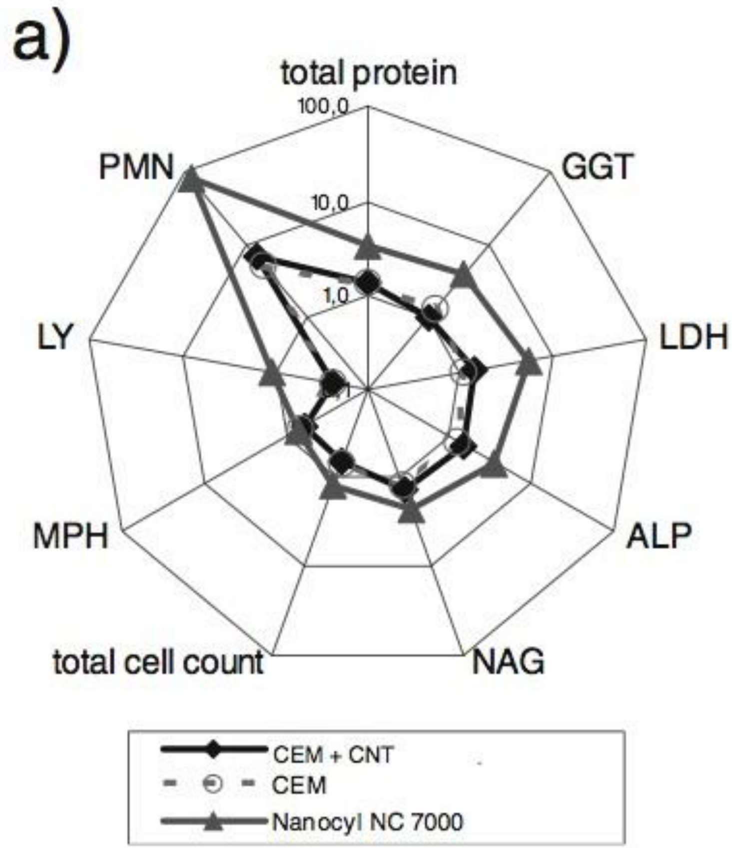
Environ Sci Technol. 2016;50:5927-34.

The Ag release of the textiles investigated occurs almost completely in the form of dissolved Ions

ENM	Nanocomposite	Target	Results	Ref
TiO_2 Ag SiO_2	Commercial paints (weathered)	Pulmonary and systemic toxicity in mice	Comparison with pristine ENM: **NEG**	Smulders, 2014
TiO_2 Ag SiO_2	Commercial paints (weathered)	Toxicity on cells of GI and immune systems	Comparison with composites w/o ENM: **NEG**	Kaiser, 2013
TiO_2 CB SiO_2	Commercial paints (sanding dust)	Pulmonary and systemic toxicity in mice	Comparison with pristine ENM: **NEG** Comparison with composites w/o ENM: **NEG**	Saber, 2012
Al-TiO_2	Commercial sunscreen (weathered)	Toxicity on *Vicia faba* cells	Comparison with pristine ENM: **NEG**	Foltete, 2011
CNT	Lab concrete and thermoplastic nanocomp (weathered)	Pulmonary and systemic toxicity in mice	Comparison with pristine ENM: **NEG** Comparison with composites w/o ENM: **NEG**	Wohlleben, 2011
CNT-NH_2	Lab epoxy-nanocomp (weathered)	Toxicity on *Drosophila* larvae	Comparison with pristine ENM: **NEG**	Ging, 2014
MWCNT	Lab epoxy-nanocomp (abrasion)	Toxicity on pulmonary cells	Comparison with pristine ENM: **NEG**	Schlagenhauf, 2015

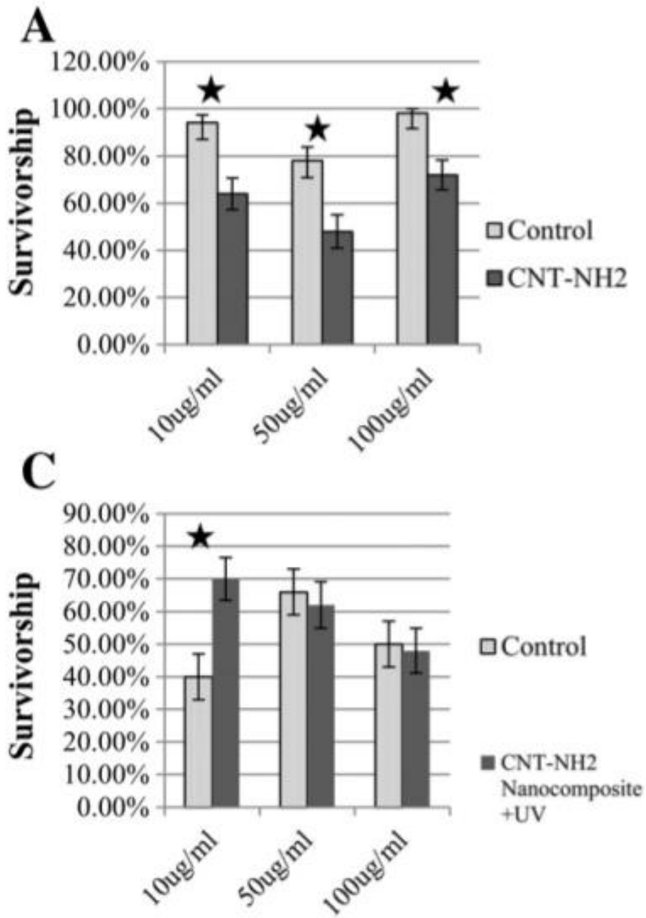
Hazard assessment of nanocomposites (1)
An in vivo study

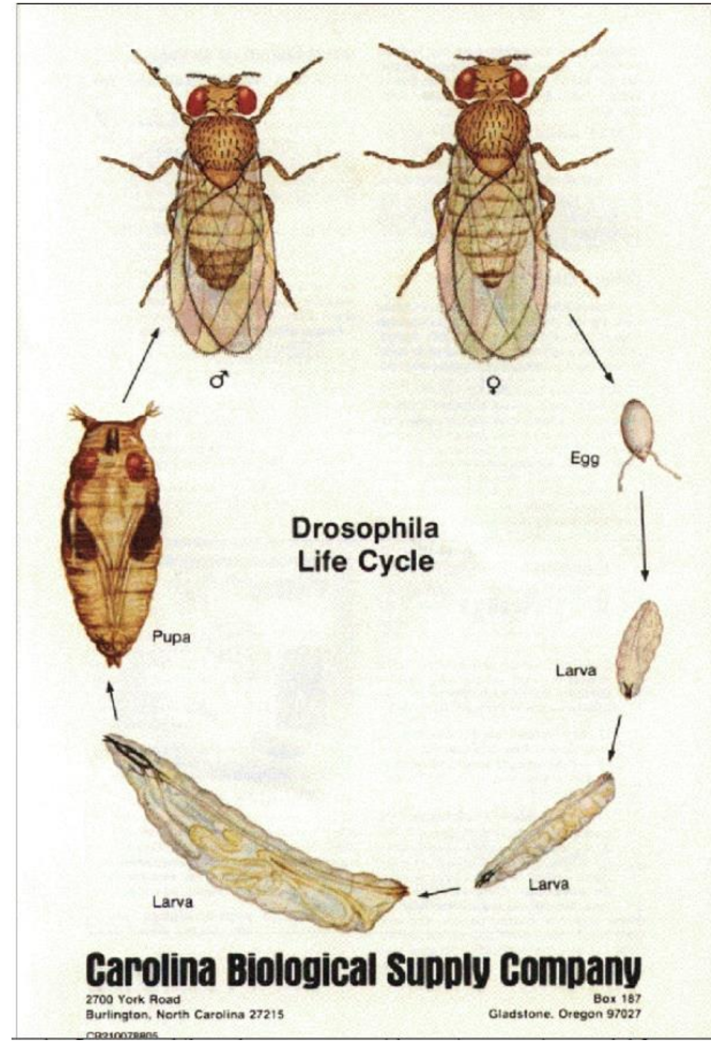
“In this pioneering and preliminary evaluation, the hazards cannot be distinguished with or without nanofiller.”



Wohlleben et al., On the lifecycle of nanocomposites: comparing released fragments and their vivo hazard from three release mechanisms and four nanocomposites. Small 7:2384–2395, 2011

Hazard assessment of nanocomposites (2)
A study in Drosophila





Development of a conceptual framework for evaluation of nanomateria release from nanocomposites: environmental and toxicological implications
Ging et al Science of the Total Environment 473–474 (2014) 9–19

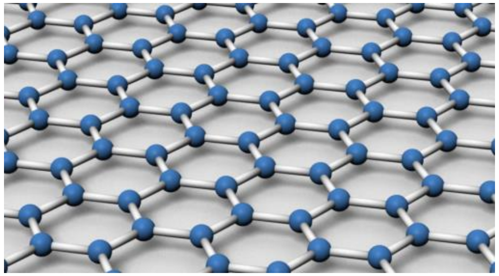
Hazard assessment of nanocomposites (3)
An in vivo study

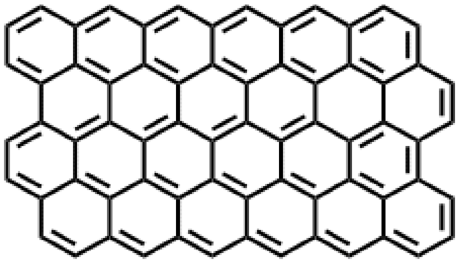
Liver lesion	EPOXY-REF	EPOXY-CNT
Foci (small) of inflammatory cells	0/54	7/54
Granuloma	0/54	3/54
Polymorphonuclear cell foci	0/54	3/54
Macrophages	0/54	10/54
Microfoci of necrosis	0/54	1/54
Eosinophilic necrosis of single hepatocytes	0/54	2/54
Hepatocytes with pyknotic nuclei	0/54	2/54
Vacuolar degeneration	2/54	9/54

Data are summarized irrespectively of treatment dose and time of sacrifice

*Epoxy **composite dusts with and without carbon nanotubes** cause similar pulmonary responses, but differences in liver histology in mice following pulmonary deposition*
Saber et al. Particle and Fibre Toxicology (2016) 13:37

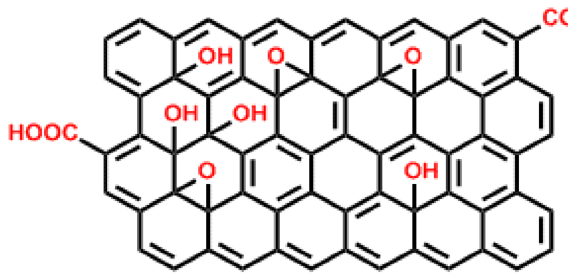
Graphene





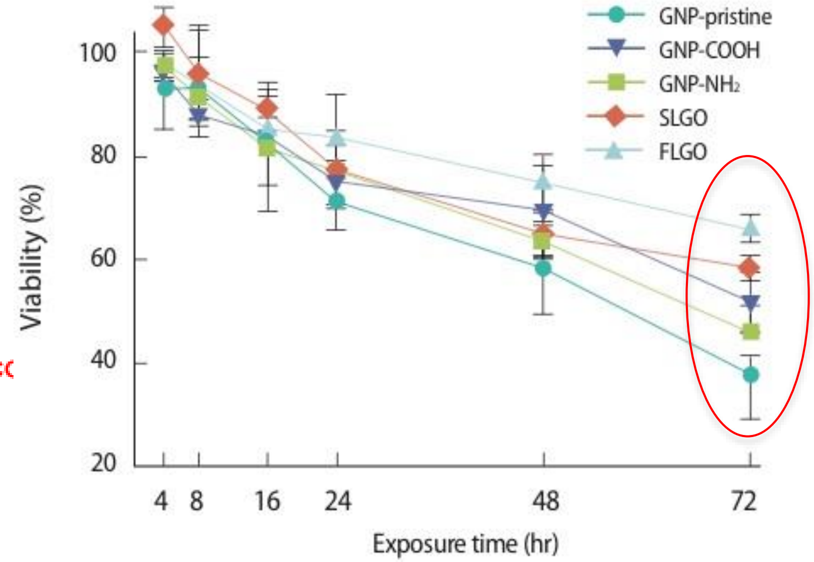
Graphene

[G0438, G0441, G0442]

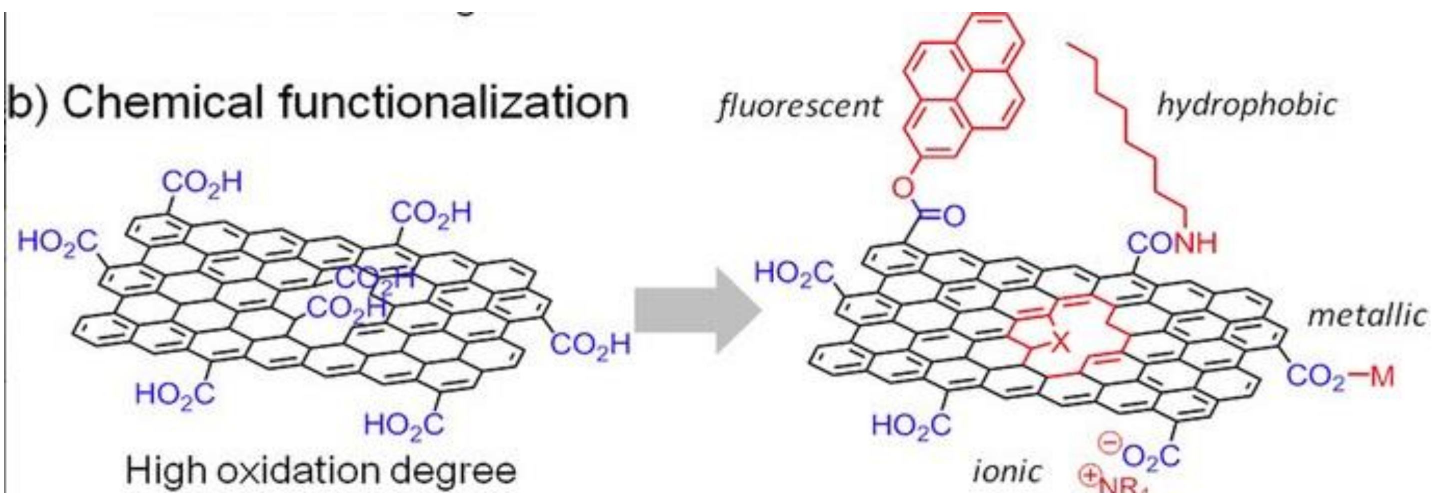


Graphene oxide

[G0443, G0444]



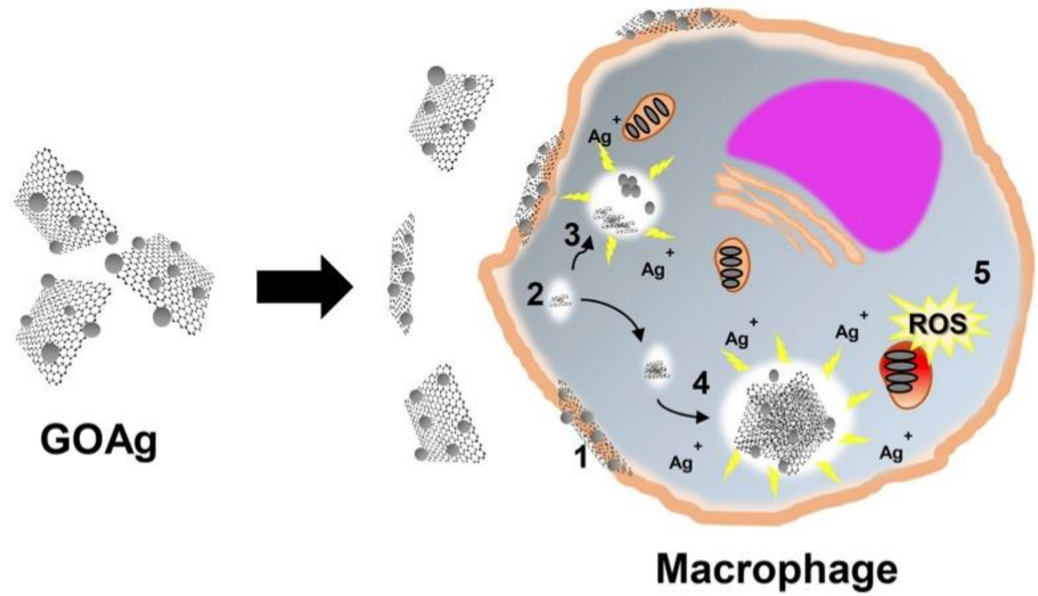
Chatterjee, Environ Health Toxicol. 2015 Jul 15;30:e2015007



Hazard assessment of graphene oxide-silver NP "nanocomposite"

GO was used as a platform to attach and stabilize AgNP

Nanomaterial (μg mL^{-1})	$IC_{50-24\,h}$
MØ J774	
GO	16.9
AgNP	8.9
GOAg	2.9
MØ peritoneal	
GO	32.9
AgNP	10.4
GOAg	3.1



Although the GOAg nanocomposite was less internalized by the macrophage cells than pristine AgNP, it was more toxic than the pristine counterparts and induced remarkable oxidative stress.

Comparative in vitro toxicity of a graphene oxide-silver nanocomposite and the pristine counterparts toward macrophages
De Luna et al., J Nanobiotechnology. 2016 Feb 24;14:12

Conclusions and perspectives

In general, available data suggest that very little amount of pristine ENM escape from degraded nanocomposites, but there may be exceptions

It is important to extend release studies to toxicological assessment

Release and toxicity studies of nanocomposites often suffer of poorly characterized materials > this could be overcome if such studies were carried out during the nanocomposite design and manufacturing phases (see the approach followed for medical applications)

Need of a standardized approach and methods for characterizing nanocomposite degradation and toxicity

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Thank you for your attention!

francesca.pacchierotti@enea.it

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